# Reactor measurement of $\theta_{12}$; Secret of the power

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We demonstrate enormous power of dedicated reactor experiment for $\theta_{12}$ with a detector placed at around the first oscillation maximum, which we call "SADO". It allows determination of $\sin^2\theta_{12}$ to the accuracy of $\simeq$2% at 1$\sigma$ CL, which surpasses all the method so far proposed. Unlike reactor $\theta_{13}$ experiments, the requirement for the systematic error is very mild, $\simeq$4%, which makes it an even more feasible experiment. If we place a detector at $\sim$60 km away from the Kashiwazaki-Kariwa nuclear power plant, 0.5 kt·yr exposure of SADO is equivalent to $\sim$100 kt·yr exposure of KamLAND assuming the same systematic error.

## 1. Introduction

After the three neutrino experiments, SK [1], K2K [2], and KamLAND [3], saw the oscillatory behavior with atmospheric and solar neutrino mixing parameters, physics of neutrino oscillation has entered into a new era. NOW2004 is so timely held that it is the first dedicated workshop to neutrino oscillations in the new era.

One of the directions which will be pursued in the new era is the precise determination of the lepton mixing parameters. Suppose that in someday we succeed to construct the "standard model of flavor mixing". Given the enormous development of particle physics in the last 30 years, it is highly unlikely that it will never happen. Less ambitious assumption is that there might be some relationship between the quark and the lepton mixing parameters, whose example is given by the quark-lepton complementarity [4]. In trying to test such theories, then, we will discover the great disparity between accuracies of measurement of mixing parameters in the quark and the lepton sectors.

The most accurately measured quark mixing angle is the Cabibbo angle, whose error is about 1.4% in $\sin^2\theta_C$ at 90% CL [5]. The most accurately measured lepton mixing angle is the solar angle, $\theta_{12}$, whose error is about 14% in $\sin^2\theta_{12}$ at the same CL [6]. Future operation of the solar and the KamLAND experiments are expected to lead to improvement only by a factor of $\sim$2 [7]. So the right question is: "are there ways to measure $\theta_{12}$ far more accurately than it is now?" and "can the sensitivity ever reach to the level comparable to the Cabibbo angle?" We answer in the positive to these questions.

It is well known for years that the best way to achieve optimal sensitivity for mixing angles is to exploit energy and baseline tuned to the oscillation maximum. (For a pedagogical exposition of this principle, see [8].) For small mixing angle $\theta_{13}$, it gives the highest chance of accessing to the unique unknown mixing angle, and the method has been widely exploited by the reactor $\theta_{13}$ experiments [9,10]. For large mixing angles $\theta_{12}$ and $\theta_{23}$, on the other hand, it allows us the best hope for realizing the highest sensitivity. In the JPARC-SK experiment, the principle is utilized to reach to the sensitivity as high as $\simeq$1-2% in $\sin^2 2\theta_{23}$ [11,12].[2]

Then, it is entirely natural to try to extend the method of tuning to the oscillation maximum

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[2]In the talk at the workshop the problem of accurate determination of $\theta_{23}$ was also addressed. But, we concentrate on $\theta_{12}$ in this manuscript because the space is quite limited. We refer [12] for the latter topics.

to precision $\theta_{12}$ measurement, and it is what we discuss in this manuscript based on [8]. See [13] for a similar but different proposal. For our purpose, the right distance is of order $L = L_{\rm OM} \equiv 2\pi E_{\rm peak}/\Delta m^2_{21} \simeq 60$ km, where $E_{\rm peak} = 4$ MeV is a peak energy of event spectrum. Let us call, for ease of frequent reference, a detector placed at around the oscillation maximum "SADO", an acronym of Several-tens of km Antineutrino DetectOr. Though our discussion is fully based on the results obtained in [8], we will present informations complementary to it. In particular, all the figures are new.

## 2. Requirements for the experimental systematic error

In order to design feasible experiments we cannot be too optimistic to the experimental systematic error. Because energy spectrum cut at $E_{\rm prompt} = 2.6$ MeV produces the systematic error of 2.3% in KamLAND [3], it is better not to do spectrum cut. But, then, we have to deal with geo-neutrino contamination, the problem addressed in detail in [8]. Fortunately, we have uncovered that we can accommodate a rather relaxed value 4% of the experimental systematic error. It should be within reach, given the current KamLAND error of 6.5%, if the fiducial volume error is better controlled and no spectrum cut is performed. It is also found that geo-neutrino contamination can be tolerable by an appropriate choice of the baseline, $L = 50 - 70$ km.

## 3. SADO sensitivity of $\theta_{12}$

Now we present SADO sensitivity of $\theta_{12}$ in Fig. 1. To make it complementary to the one given in [8], we plot the errors of $\sin^2\theta_{12}$ as a function of $\Delta m^2_{21}$. Because of possible change in the best fit value of $\Delta m^2_{21}$ in the future, it would be useful to have such an information. Since the vacuum oscillation probability is a function of $\Delta m^2_{21} L$, the information is (not quite equivalent but) complementary to the $L$-dependence of the error given in Fig.3 of [8].

As we see in Fig. 1, the SADO sensitivity can reach to $\simeq$2% in $\sin^2\theta_{12}$ at 1 $\sigma$ CL ($\simeq$3% in 90% CL). Therefore, it can reach to the level roughly comparable to that of the Cabibbo angle. It is also remarkable that the sensitivity remains the same within $\pm$20% for a wide range of $\Delta m^2_{21}$ currently allowed by the KamLAND data. It in turn implies that a wide range of baseline, 50-70 km from the reactor complex, is suitable, allowing a variety of possibilities for site selection.

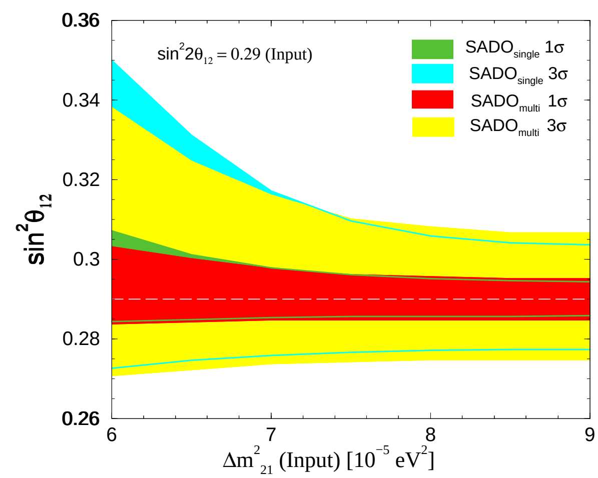


Figure 1. The error of $\sin^2\theta_{12}$ (1 degree of freedom (DOF)) as a function of $\Delta m^2_{21}$ expected by SADO at 54 km away from Kashiwazaki-Kariwa nuclear power plant with 60 GW$_{th}$·kt·yr exposure. SADO$_{\rm multi}$ and SADO$_{\rm single}$ refer, respectively, the cases with and without other 15 reactors. The geo-neutrinos are treated by the Fully Radiogenic model [8].

For remaining issues like dependence of sensitivity on geo-neutrino models and running time, the effects of surrounding reactors, as well as detailed analysis procedure with a careful stability check of the statistical method, see [8].

## 4. KamLAND vs. SADO

KamLAND is the marvelous experiment that has settled the solar neutrino problem which lasted for nearly 40 years by observing deficit of antineutrinos from reactors located at 100-200 km from Kamioka [14]. It will run ~10 more years in the future. Therefore, unless SADO supersedes

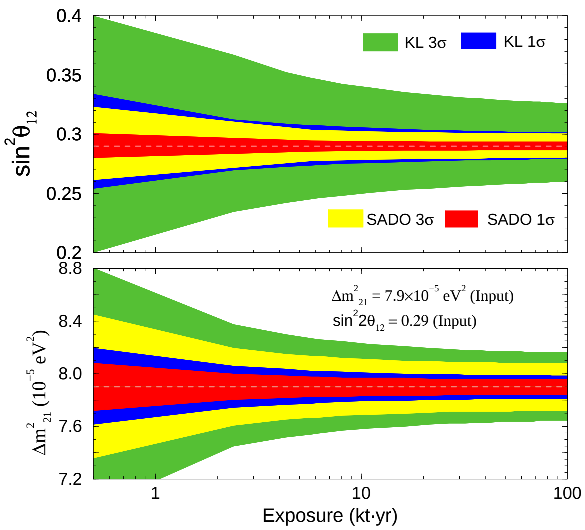


Figure 2. Accuracies of determination of $\sin^2\theta_{12}$ (upper panel) and $\Delta m^2_{21}$ (lower panel) reachable by KamLAND and SADO (both 1 DOF) are compared with the same systematic error of 4%. The geo-neutrino contribution was switched off.

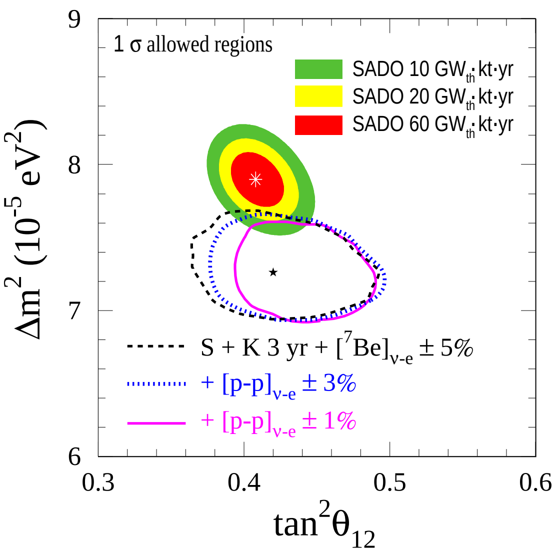


Figure 3. SADO's sensitivity contours are plotted in $\tan^2\theta_{12}$-$\Delta m^2_{21}$ space and are overlaid on Fig.6 of [7], in which the sensitivities of solar-KamLAND combined method are presented. The errors are defined both with 2 DOF.

the sensitivity of KamLAND with large margin there is no sense of talking about such an expensive new project. Moreover, there is a real merit of the KamLAND-SADO comparison; It should prove (or disprove) how powerful is the method of tuning the baseline distance.

We present in Fig. 2 KamLAND vs. SADO comparison of the sensitivities as a function of kt·yr, assuming that SADO is placed at 54 km away from the Kashiwazaki-Kariwa nuclear power plant. We observe that to reach the same accuracy of $\sin^2\theta_{12}$ achieved by SADO in a short exposure of 0.5 kt·yr, KamLAND would take $\sim$100 kt·yr. Notice that both detectors receive the same neutrino flux from all the 16 reactors in Japan. Therefore, the difference in their sensitivities reflects just their locations and the result testifies for the power of the method of tuning to the first oscillation maximum.

## 5. Solar plus KamLAND vs. SADO

A burning question by the readers may be whether SADO can surpasses the great sensitivity to be achieved jointly by KamLAND and precision measurement of solar neutrino fluxes, in particular, $^7$Be and pp neutrinos. In Fig. 3, we present the results obtained by Bahcall and Peña-Garay [7], and the corresponding sensitivity to be achieved by SADO [8], both plotted in terms of $\tan^2\theta_{12}$ following [7]. As you can observe from the figure, SADO has potential of superseding the solar-KamLAND combined method in sensitivities not only to $\theta_{12}$ but also to $\Delta m^2_{21}$. Notice that the solid (purple) line of the solar-KamLAND method assumes total experimental error of 1% for *pp* neutrino observation, and therefore it may be called as an ultimate accuracy achievable by the method.

It must be emphasized that the better accuracy of $\theta_{12}$ by SADO *does not* lower the value of planned low-energy solar neutrino experiments. See [15] for overview of such experiments. Since the uncertainty of $\theta_{12}$ may be the largest source of the systematic error in such experiments, SADO does indeed helps them by decreasing the major part of the systematic error. Therefore, it will facilitate highly accurate determination of solar

neutrino fluxes, in particular the *pp* flux, which is most important to probe structure of the principal solar engine.

## 6. Physics implications

Precision measurement of $\theta_{12}$ has a number of interesting physics implications not only in particle physics point of view but also in observational solar astrophysics and geo-physics. It will open a new era of lepton mixing parameter determination with the accuracy comparable with quark sector. In observational solar physics, precision measurement of $\theta_{12}$ plays a key role for accurate flux determination, and is indispensable for model-independent test of the standard solar model. In geo-physics context, it will help to remove "reactor background" of geo-neutrino measurement at KamLAND and at Borexino [16]. It will contribute to future neutrino experiments, e.g., by decreasing the ambiguity in observing CP violation effect which comes from uncertainties of other mixing parameters. It improves the accuracy of the test of CPT invariance in the lepton sector and various exotic hypotheses including flavor changing neutral current. See [8] for more details.

## 7. Concluding remarks

In the talk we emphasized that there exists a coherent view for measuring the large mixing angles, $\theta_{12}$ and $\theta_{23}$, precisely by tuning the baseline distance. Quite unfortunately, in the case of $\theta_{23}$ the enormous accuracy of $\sin^2 2\theta_{23}$ determination *does not* lead to the precise determination of $\theta_{23}$. It is due to the doubly bad luck we suffer, one by the large Jacobian at the nearly maximal mixing, and the other by the octant degeneracy of $\theta_{23}$, as discussed in detail in [12].

On the other hand, the situation for $\theta_{12}$ is comfortably good as we have seen above. The SADO type experiment is feasible with modest requirement of 4% for the experimental systematic error. Then, the last message to the experimentalists; Why don't you attempt to carry out such experiment?

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